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Progress Report on Proposal NAGW-4156: "Planet Forming Protostellar Disks"

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1 Accomplishments

The main thrust of the proposal is to investigate mechanisms by which young binary stars interact with disks formed from relics of the star formation process. These binary/disk interactions affect both the evolution of the disks and the binary. We have been analyzing the effects of such interactions by using both analytical methods and numerical simulations. A long-term goal is to apply these techniques to the study of planet-disk interactions. In the short-term we aim to compare our results with recent observations of circumstellar and circumbinary disks (see review by Mathieu 1995). In doing so, we can test aspects of our models that relate to protostellar and protoplanetary disk properties and test the theory of resonant disk interactions.

Our first results covered by this grant concerned the sizes of gaps in disks and were published in the *Astrophyical Journal* (Artymowicz and Lubow 1994). The gaps are created by tidal forces due to the binary. We investigated the gap sizes as a function of the binary eccentricity and separation, and the disk turbulent viscosity. These results have provided a basis for understanding observed disk mass depletion in young binaries (e.g., Jensen et al 1996). The observed circumbinary disk inner edge location around GG Tau has been used, together with our models, to infer possible orbital parameters for the binary (Dutrey et al 1994; Roddier et al 1996).

More recently, we have found that circumbinary disks exhibit distinct behaviors, depending on whether they are cold (disk thickness to radius ratio $H/R < 0.05$) or warm (disk thickness to radius ratio $H/R > 0.05$). In the case of cold disks, we find the the inner edge of the circumbinary disk can become eccentric and precess, but no material can actually flow through the gap onto the embedded stars. For warm disks, we find little evidence for disk eccentricity, but instead find that material can cross the gap in the form of gas streams. We described preliminary results in a conference proceeding (Artymowicz and Lubow 1995).

Further investigations were carried out to understand the binary orbital evolution, in terms of 1D numerical models, 2D SPH simulations, and analytic models. The 1D model was useful for determining the evolution over very long timescales. The 2D SPH results provide information about the spatial disk structure. The analytic models provide an important cross-check of the numerical results, but are somewhat limited in parameter space. These results and others were presented at a NATO Advanced Study Institute (Lubow and

Artymowicz 1996).

We have further studied the properties of the gas streams that allow material to flow across the gaps. This process is important in determining whether binary stars can continue to gain mass once gap formation occurs. We have found that these gas streams will strike the binary in a time-modulated manner that depends on the binary eccentricity and mass ratio. Such stream impacts should be observeable and we have calculated the time-dependence of the resulting emission. These results have been submitted for publication in *Astrophysical Journal Letters* (Artymowicz and Lubow 1996). In addition, we have developed a video of our simulations of the time-variable mass flow in the streams.

The recent discoveries of planets around solar-type stars has caused us to investigate the role of tidal interactions in such systems. We have investigated the orbital stability of the planet around 51 Peg (Mayor and Queloz 1995; Marcy and Butler 1995). Because the planet is relatively close to its central star, a number of issues arise about the planet-star orbital interactions. Mayor and Queloz (1995) raised several important questions about the possible role of tidal interactions in 51 Peg. We investigated many of those issues. The basic result is that the orbit of 51 Peg is unstable, but the tidal interactions are quite weak. As a result, the instability is important only over times much longer than the age of the system. In addition, we mapped out the range of orbital parameters for which planets could survive orbital instability over the system age. These results and others are contained in a paper submitted to the Astrophysical Journal (Rasio et al 1996).

In addition to the above publications, S. Lubow presented an invited talk at the 1996 AAS Division of Dynamical Astronomy Meeting in Washington, D.C. that reviewed the results described above. S. Lubow was also a member of the scientific organizing committee for the OSS-supported conference "Planet Formation in the Binary Environment".

2 Future Plans

During the next year, we plan to investigate the role of gas stream on binary evolution. In the absence of gas streams, as in the case of cold disks, the binary orbit will decay. We will be trying to determine whether the effects of the gas stream can cause the binary orbit to expand and cause the eccentricity to grow.

We also plan to complete and publish our results on cold disks.

Other dynamical processes involving the 51 Peg system are currently under investigation. These include a determination of the spin evolution of the planet and possible orbital instability that may have occured during earlier phases of the system.

3 Publications Resulting From Grant

Artymowicz, P. and Lubow, S.H. 1994, "Dynamics of Binary-Disk Interaction I: Resonances and Disk Gap Sizes", ApJ, 421, 651.

Artymowicz, P. and Lubow, S.H. 1995, "Interaction of Young Binaries with Protostellar Disks", in "Disks and Outflows Around Young Stars", A. M. Quetz, J. Staude, and S. Beckwith, Berlin: Springer, 115 (p. 242 in CD-ROM version).

Lubow, ~~S.H.~~ and Artymowicz, P. 1996, "Young Binary Star/Disk Interactions", to appear in "Evolutionary Processes in Binary Stars", Cambridge.

Artymowicz, P. and Lubow, S.H. 1996, "Dynamics of Binary-Disk Interaction II: Mass Flow Through Gaps", ApJ Letters, submitted.

Rasio, F., Tout, C., Lubow, S.H., and Livio, F. 1996, "Tidal Decay of Close Planetary Orbits", ApJ, submitted.

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Dutrey, A., Guilloteau, S., and Simon, M. 1994, AA, 286, 149.

Jensen, E., Mathieu, R.D., Fuller, G.A. 1995, ApJ, 458, 312.

Mathieu, R.D. 1994, ARAA, 32, 465.

Marcy, G. and Butler, R.P. 1995, IAU Circ. 6251.

Mayor, M. and Queloz, D. 1995, Nature, 378, 355

Roddier, C., Roddier, F., Northcott, M.J., Graves, J.E., Jim, K. 1996, ApJ Lett, in press.